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ORCHARD MICROCLIMATIC OBSERVATIONS IN USING SOIL-APPLIED COAL DUST FOR FROST PROTECTION

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ABSTRACT

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This study was conducted at the Appalachian Fruit Research Station, Kearneysville, West Virginia, to determine the effectiveness of using soil-applied coal dust in modifying the orchard microclimate. Coal dust was applied on 5 April 1985 at a rate of 18.1 Mg ha^{-1} to the bare soil surface of a 1.4-ha peach (*Prunus persica* (L.) Batsch) planting. An adjoining 1.4-ha planting served as a control to which nocturnal net radiation (*RN*), soil heat flux (*G*), orchard canopy energy storage (*St*), sensible heat flux (*H*) and orchard temperature measurements were compared both before and after the coal application. Both plantings consisted of alternating 3-m wide soil—3-m wide grass strips with trees planted in the soil strip.

Under typical radiative frost conditions (*RN* of $-60\ W\ m^{-2}$), the coal dust enhanced the radiative loss by $5\ W\ m^{-2}$. This loss, assumed to result from a uniform temperature change of the orchard, was equivalent to a 1°C increase in orchard temperature. The increased radiative loss was due to higher air, canopy and soil temperatures. No effect was found in *G* or *St* due to the coal dust treatment. However, a greater downward transfer of sensible heat (5—8 $W\ m^{-2}$ depending on method used to estimate *H*) to the orchard was found by using the coal dust. This increased flux was in response to larger air temperature gradients established near the canopy top following the coal application.

The direct effect of using coal dust was measured in an increase in bud temperature. Under radiative frost conditions, an increase of 0.5°C in bud temperature was found.

INTRODUCTION

Frost protection is of concern to orchardists because of the financial loss due to bud or fruit damage and the incurrence of costs related to protection. Wind machines, oil burners and overhead sprinklers are commonly used throughout the U.S.A. for frost protection. This equipment is costly because of the labor, maintenance, or fuel required for their operation (Blizzard et al., 1985). Feasible, yet economic means of moderating orchard temperatures are still sought.

Modification of the orchard microclimate can be achieved under certain atmospheric conditions. For example, modification is realistic under radiative frost conditions whereas under advective frosts little protection is realized. The inversion layer, developed under radiative frost conditions and extending to heights of several hundred meters, can usually be modified so as to mix the warm air at greater heights with cooler air near the surface. The

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degree of modification depends on the strength and height of the inversion (Schultz, 1962). Under advective frosts, wind power, sprinklers and to some extent oil burners, are of little value in moderating orchard temperatures due to atmospheric instability and the duration of low temperatures (Leyden and Rohrbaugh, 1963; Gerber et al., 1974).

An alternate method of frost protection is based on the principle that the soil is a heat reservoir. Increasing heat flow into the soil during the day results in greater heat flow out of the soil at night. Altering the heat flow into and out of the soil has been evaluated using mulches, ground covers and plastics, (Waggoner et al., 1960; Leyden and Rohrbaugh, 1963; Ludlow and Fisher, 1976). Mulches and ground covers are of little value for frost protection because they insulate the soil and thus diminish heat transfer to and from the soil. However, plastics can be made to alter heat flow processes of the soil by retarding heat loss at night until the plastic is removed. Fritton and Martsolf (1981) found that for a short time after removal of plastic covers, bare soils maintained a 10°C higher surface temperature and a two-fold increase in heat flow compared with soils not covered with plastic. Welles et al. (1978) reported that a 10°C increase in soil surface temperature reduced the burn rate of orchard heaters by 25% and saved an additional 35% of the blossoms. However, practical means of trapping and storing solar energy in the soil have not been realized.

The purpose of this study was to determine the effectiveness of using soil-applied coal dust in altering the orchard microclimate under radiative frost conditions. The radiative properties of coal are desirable in capturing solar energy and releasing terrestrial energy. The cost also makes it a feasible economic alternative to commonly used frost protection methods.

MATERIALS AND METHODS

The study was conducted at the Appalachian Fruit Research Station located in the central Shenandoah Valley of West Virginia. The soil type was a Hagerstown silt loam and the gently rolling topography was characteristic of the fruit growing area of the northeastern U.S.A.

Two adjoining 1.4-ha peach (*Prunus persica* (L.) Batsch) plots were used to study the effect of coal dust on the orchard microclimate. Trees were planted in 1980 in northeast—southwest bare soil strips at a population of 300 trees ha^{-1}. The soil strips and intervening grass alleys, each 3 m in width, of both plots were maintained as needed. Within each plot, a 670-m^2 control area was established in which micrometeorological factors were monitored. The control area was located in the center of each treatment plot; the slopes between plots differed by $< 1\%$ and had the same aspect.

Soil heat flow plates and copper-constantan thermocouples were installed in the soil in November 1984. The instruments were placed on an east—west transect ~ 1.5 m apart. At four locations on the transect in each plot, soil heat flow plates were buried at 5 cm and thermocouples at 1, 5 and 15 cm. Three of the measurement locations were in the soil strip (under canopy, edge of canopy and between adjacent trees near the edge of the soil—grass border) and one in the grass alley.

Instruments to monitor the above-ground environment were set up in March 1985. An environmental tracking system (ETS) was used in each plot to transport two net radiometers, two anemometers and two temperature masts across the orchard top. The instruments were connected to a platform mounted on door tracks permitting movement of the instruments across a 10-m traverse of the orchard top. An electric motor and chain propelled the instrument platform. The tracks were suspended 3 m above the ground surface. The net radiometers and temperature masts, consisting of dry bulb three-junction thermopiles at three levels spaced 0.25 m apart, were positioned at 0.5 and 0.25 m above the canopy, respectively. The masts were constructed of 1.3-cm O.D. PVC pipe wrapped with insulation. Stationary temperature masts were placed in the center of the grass alley and midway between trees in the soil strip. Construction was similar to the masts used on the ETS except temperatures were monitored at four levels spaced 0.5 m apart. The lowest level at which temperatures were monitored was 0.45 m above the effective surface. An air hose, attached to the PVC pipe and a vacuum pump, was used to ventilate the dry bulb thermopiles. Calibration of thermopiles was made at selected times during the evening and morning of the nocturnal period when data were collected. The anemometers were vertically spaced 0.25 m apart.

Tree temperatures were measured concurrently with other micrometeorological measurements. In each treatment plot, thermocouples were attached to six flower buds and three stems (total of three trees used per plot) located in the canopy at 1.5 m above the soil. The reference temperature of a wooden dowel, 1 cm O.D. and placed at 1.5-m in the canopy, was monitored.

All instruments were connected to a datalogger (Campbell Scientific Inc. CR7)* programmed to record data every 5 min. Data were collected for 1 week prior to the coal dust application and on nights when conditions were conducive for radiation frosts. These data were later summarized for half-hourly periods.

By April 1985, when this study was initiated, plot differences were apparent due to grass (*Festuca arundinacea* Schreb.) emergence in the soil strips of one plot. The soil strips of this plot had developed a trashy appearance (hereafter referred to as trashy surface) with ~ 20% grass cover. In order to separate the treatment (coal dust) effect from inherent plot differences, soil bulk density measurements were taken at the 0—5 and 5—15-cm depths at 27 locations within each control area. In addition, 1 week prior to the coal application, micrometeorological measurements were taken.

Coal dust was applied on 5 April 1985 at a rate of 18.1 Mg ha^{-1} to the

* Mention of a company product is for reader information only and does not imply endorsement or preferential treatment by any party involved.

bare soil surface of one plot. A slurry of coal dust, water and fiber mulch, which acted as a suspending agent for the coal, was sprayed onto the soil surface using a hydroseeder. Approximately $1\,\mathrm{Mg\,ha^{-1}}$ of fiber mulch was applied to the bare soil surface in the process. The trashy surface of the other plot was left untreated.

Energy budget analysis

The energy budget is by definition:

$$RN = G + H + LE + St + P$$

where RN is net radiation, G is soil heat flux, H is sensible heat flux, LE is latent heat of evaporation, St is storage and P is the energy utilized in net photosynthesis. Generally, P is very small and omitted from the energy budget calculations (Thom, 1975). Latent heat of evaporation is assumed to be negligible during the time period 20.00 – 06.00 EST when we collected data. The signs of RN, G and St are negative when more energy leaves the orchard than is incoming; H is negative when directed to the orchard.

Soil surface heat flux was estimated using the following method:

$$G(0) = G(5) + {}_0\!\int^5 c_\mathrm{v}\,(\Delta T/\Delta t)\,\mathrm{d}z$$

where $G(0)$ and $G(5)$ were the respective soil heat fluxes at the surface and 5 cm, c_v was volumetric heat capacity, T was soil temperature, t was time and z was depth. Temperatures at 1 and 5 cm were averaged to obtain a mean temperature for the surface layer of soil. Heat flux was assumed to be the same within 1 m of the tree trunk, from 1 m to the canopy edge, outside the canopy in the bare soil or trashy strip and in the grass alley. A spatially averaged heat flux for the soil area was estimated by averaging the heat flux at each of the three soil locations per plot over the area which they represented; heat flux for the orchard area was estimated by averaging heat flux for the one grass and three soil locations over their representative area.

Sensible heat flux was estimated using the aerodynamic method:

$$H = -\rho c k^2 (Z - D)^2 (\mathrm{d}U/\mathrm{d}Z)(\mathrm{d}T/\mathrm{d}Z)(K_\mathrm{h}/K_\mathrm{m})\Phi_\mathrm{m}^{-2}$$

where ρ was the density ($1.293\,\mathrm{kg\,m^{-3}}$) and c the specific heat ($1003\,\mathrm{J\,^\circ C^{-1}\,kg^{-1}}$) of air, k was von Karman's constant of 0.4, D was the zero plane displacement (1.8 m) as determined from Stanhill (1969), U was wind speed, T was air temperature, K_h and K_m were the respective exchange coefficients for sensible heat and momentum transfer and Φ_m was the stability function. The stability function and ratio of the exchange coefficients were determined for unstable atmospheric conditions according to Dyer and Hicks (1970); for stable conditions they were determined using the method of Webb (1970). Atmospheric stability was evaluated using Richardson's number, defined as:

$$Ri = [g/(dT/dZ)]/[T(dU/dZ)^2]$$

where g was the gravitational acceleration ($9.8\ m\ s^{-2}$) and T was the mean absolute temperature. One wind speed and six air temperature gradients above the canopy in each plot were computed for determining atmospheric stability and sensible heat flux. Sensible heat flux was also determined as a residual in the energy budget and compared to those obtained using the aerodynamic method.

Energy storage in the orchard canopy was evaluated using the equation:

$$St = St_t + St_a$$

where St_t and St_a were the respective sensible heat storage of the tree and air. Only sensible heat storage was accounted for in this study, considering that latent heat storage in the air is a small part of the total storage (Stewart and Thom, 1973). Orchard canopy heat storage can be formulated as:

$$St = -(m_w c_w \Delta T_w + m_a c_a \Delta T_a)$$

where m_w and m_a were the respective masses of wood and air, c_w and c_a were the respective specific heats of wood ($2.5\ J\ g^{-1}\ {}^\circ C^{-1}$) and air ($1.0\ J\ g^{-1}\ {}^\circ C^{-1}$) and T_w and T_a were the respective temperatures of wood and air. For this study, we assumed that a change in the wooden dowel temperature represented a change in the temperature of the tree. Air temperature changes were estimated by averaging eight air temperature readings per plot, four readings each over the soil (or trashy) surface and grass alley at four different heights.

Data analysis

A determination was made both before and after the coal treatment of the relationship of the same environmental factor between plots. For example, the relationship of *RN* on the bare soil plot versus *RN* on the trashy plot was determined both before and after the coal application. This procedure was used on all environmental data collected on radiation frost nights between 20.00 and 06.00 EST. Generally, all relationships had an R^2 value of $\geqslant 0.95$.

RESULTS AND DISCUSSION

In late spring of 1985, three nights were characterized by meteorological conditions conducive to the occurrence of radiation frosts (i.e., wind speeds $< 2\ m\ s^{-1}$ and clear skies). These nights included 9 and 17 April and 3 May. The minimum air temperature associated with each of these dates was -7.1, 3.4 and 1.5°C, respectively.

Maximum fluxes of energy budget components and minimum soil, air and canopy temperatures on the bare soil and trashy plots for two nights before and the three nights after the coal application are presented in Table I. Net

TABLE I

Maximum fluxes of energy budget components and minimum soil (1-cm depth), air and canopy temperatures on the bare and trashy orchard floor-managed plots for selected days. Coal dust was applied to the bare plot on 5 April 1985

Microclimatic variable	Plot	Energy flux/Temperature				
		April				May
		2	3	9	17	3
RN ($W m^{-2}$)	Bare	−45	−59	−64	−61	−69
	Trashy	−45	−60	−60	−62	−66
G ($W m^{-2}$)	Bare	−28	−27	−35	−30	−26
	Trashy	−21	−20	−28	−28	−24
St ($W m^{-2}$)	Bare	− 2	—	− 5	− 5	− 6
	Trashy	− 2	—	− 6	− 6	− 7
H ($W m^{-2}$)	Bare	−30	−43	−38	−43	−50
	Trashy	−35	−48	−36	−35	−45
Soil T* (°C)	Bare	3.8	3.6	0.9	9.1	10.6
	Trashy	4.1	4.0	0.6	7.6	9.7
Air T* (°C)	Bare	1.8	—	− 7.8	3.2	1.3
	Trashy	1.8	—	− 7.8	3.4	1.5
Canopy T* (°C)	Bare	2.7	—	− 6.6	4.1	3.7
	Trashy	3.0	—	− 6.6	4.1	3.7

* Values represent average minimum of soil temperatures at four locations (Soil T), air temperatures from two profile measurements at four different heights (Air T) and the dowel, stem and bud temperatures (Canopy T).

radiation (RN) of $-60\,W\,m^{-2}$ was common on nights when radiative frost conditions prevailed (Table I). The maximum radiative loss recorded during the course of the study was $-69\,W\,m^{-2}$. Soil surface heat flux (G) averaged over the orchard area was highest on 9 April at $-35\,W\,m^{-2}$; this was ~ 50% of RN. Sensible heat flux (H) was downward (due to an inversion above the orchard top) and was highest on 3 May at $-50\,W\,m^{-2}$. This flux corresponded to ~ 80% of RN. Generally, soil surface and sensible heat flux accounted for one- and two-thirds of the net radiative loss, respectively. Little of the loss was accounted for by a change in the orchard canopy heat storage (< 10% of RN).

Relationships of the microclimatic variables between plots both before and after the coal dust application are reported in Table II. The RN slopes were significantly different and indicated that RN decreased (more negative) following the coal application. This relationship is illustrated in Fig. 1. A greater loss of energy from the orchard resulted when the bare soil was treated with coal dust. Under conditions when RN was $-60\,W\,m^{-2}$ on the trashy plot, the 90% confidence interval (CI) of the predicted RN on the

TABLE II

Microclimatic relationships between the bare and trashy orchard floor-managed plots both before and after the application of coal dust to the bare plot

Microclimatic variable	Relationship between plots					
	Before coal			After coal		
	Slope[a]	Intercept[a]	r^2	Slope	Intercept	r^2
RN (W m^{-2})	0.89 ± 0.02 a	−2.8 ± 0.5 b	0.99	0.94 ± 0.01	−5.2 ± 0.6	0.99
G (W m^{-2})						
Orchard	1.20 ± 0.06	−0.7 ± 1.1	0.91	1.24 ± 0.04	1.9 ± 1.0	0.94
Soil	1.29 ± 0.06	−1.3 ± 1.3 b	0.93	1.42 ± 0.06	4.2 ± 1.6	0.91
St (W m^{-2})	1.07 ± 0.05	0.2 ± 0.3	0.97	0.99 ± 0.05	−0.2 ± 0.2	0.90
H^b (W m^{-2})						
Residual	0.93 ± 0.02	3.9 ± 0.5 b	0.99	0.98 ± 0.04	0 ± 1.2	0.93
Aero	0.82 ± 0.05	−0.4 ± 0.4 b	0.94	0.99 ± 0.05	−4.2 ± 1.4	0.92
Soil T 1-cm (°C)						
Under canopy	0.94 ± 0.02	−0.6 ± 0.1 b	0.99	0.89 ± 0.01	0.9 ± 0.1	0.99
Canopy edge	0.94 ± 0.01 a	0.2 ± 0.1 b	0.99	1.12 ± 0.02	1.8 ± 0.2	0.97
Between canopies	1.22 ± 0.02 a	−1.8 ± 0.1	1.0	1.06 ± 0.01	−1.6 ± 0.1	0.99
Grass alley	0.69 ± 0.14	2.2 ± 1.1	0.93	0.74 ± 0.04	3.7 ± 0.5	0.92
Air T (°C)						
Orchard	0.99 ± 0.01	0 ± 0 b	1.0	0.98 ± 0.01	−0.3 ± 0.1	0.99
Above soil						
45 cm	1.01 ± 0.03	−0.5 ± 0.2 b	0.96	1.03 ± 0.01	0 ± 0	1.0
95 cm	1.07 ± 0.02 a	−0.3 ± 0.1 b	0.99	1.01 ± 0.01	0.1 ± 0	1.0
145 cm	1.02 ± 0.01 a	−0.1 ± 0.1 b	0.99	0.98 ± 0.01	−0.4 ± 0	1.0
195 cm	0.94 ± 0.02 a	−0.2 ± 0.1 b	0.99	1.01 ± 0.01	−0.4 ± 0	1.0
Canopy T (°C)						
Dowel	1.04 ± 0.02	−0.5 ± 0.2	1.0	1.02 ± 0.01	0 ± 0.1	0.98
Stem	1.01 ± 0.01	−0.2 ± 0.1	0.99	0.99 ± 0.01	0 ± 0	0.99
Bud	1.01 ± 0.01 a	−0.3 ± 0.1 b	1.0	1.05 ± 0.01	0.2 ± 0.1	0.99

[a] a, b indicate the slope and intercept significantly different at $P = 0.10$. [b] H determined by the residual and aerodynamic (aero) methods.

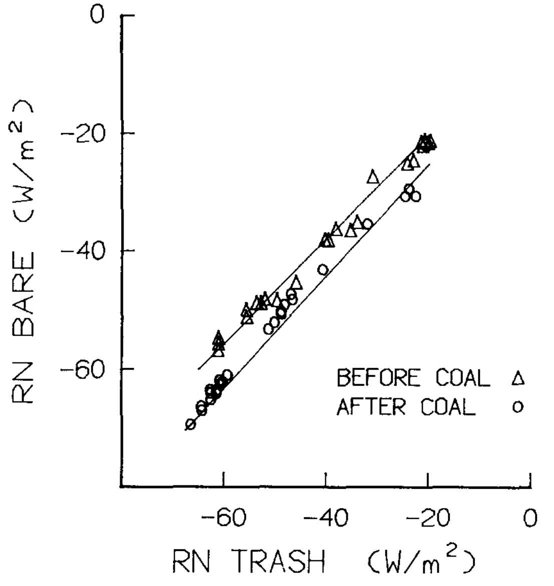

Fig. 1. Relationship between net radiation (*RN*) on the bare versus trashy orchard floor-managed plots before and after the application of coal dust to the bare plot.

bare soil plot before and after the coal application was respectively -54 to -58 and -59 to $-64\,W\,m^{-2}$ (Table III). The increased radiative loss from the bare soil plot following the coal application was $5\,W\,m^{-2}$ under these conditions. Provided this flux resulted from a uniform temperature change of the orchard, an increase of about 1°C would be required. This degree of protection is equivalent to other frost protection methods utilizing soil management strategies (Leyden and Rohrbaugh, 1963; Bridley et al., 1965; Gerber et al., 1974).

The increased loss of energy from the orchard following the application of coal dust was not accounted for by a rate of change in the heat storage of the orchard canopy—soil volume (orchard canopy or soil heat storage). Generally the orchard canopy storage term is negligible for relatively short vegetation such as orchard trees used in this study (Thom, 1975). Soil surface heat flux, averaged over either the soil area or the entire orchard area, was not affected by the coal dust application (Table II). This finding appeared anomalous because of the known radiative characteristics of black surfaces. However, the data of Qashu and Evans (1967) support these findings. Using coke to study its effect on soil temperatures in Arizona, they found that daytime soil temperatures increased to a depth of 8 cm directly below a 0.4-cm thick mulch. No temperature difference at any depth was noted near sunset or sunrise using the coke mulch. Other soil admendments have been shown to have little affect on *G*. Stanhill (1965) reported that *G* was unaffected by a surface application of magnesium carbonate; however,

TABLE III

Confidence intervals (90%) of microclimate variables in the bare soil orchard plot both before and after coal dust was applied. Predicted values based on typical energy fluxes and temperatures in the trashy orchard plot under radiative frost conditions

Variable	Trashy plot	Predicted bare plot			
		Before coal		After coal	
		Low	High	Low	High
RN ($W m^{-2}$)	−60	−54.0	−58.2	−59.4	−64.0
G ($W m^{-2}$)					
Orchard	−20	−20.6	−28.8	−19.6	−26.2
Soil	−25	−28.4	−38.7	−25.8	−36.8
St ($W m^{-2}$)	− 5	− 4.3	− 6.1	− 4.4	− 5.8
H[a] ($W m^{-2}$)					
Residual	−30	−22.3	−25.7	−25.6	−33.3
Aero	−30	−21.7	−28.3	−28.8	−39.1
Soil T 1-cm (°C)					
Under canopy	5	3.8	4.4	5.1	5.6
Canopy edge	5	4.7	5.1	6.9	7.8
Between canopies	5	4.0	4.6	3.5	4.0
Grass alley	10	3.4	14.7	9.5	12.7
Air T (°C)					
Orchard	0	0	0	− 0.4	− 0.3
Above soil					
45 cm	0	− 0.9	− 0.2	− 0.1	0.1
95 cm	0	− 0.5	− 0.1	0	0.2
145 cm	0	− 0.2	0.1	− 0.4	− 0.3
195 cm	0	0	0.4	− 0.5	− 0.3
Canopy T (°C)					
Dowel	0	− 0.9	− 0.1	− 0.1	0.1
Stem	0	− 0.4	− 0.1	− 0.1	0
Bud	0	− 0.5	− 0.1	0.1	0.3

[a] H determined by the residual and aerodynamic (aero) methods.

differences were observed in RN, evaporation and H due to the carbonate application. Fritton and Martsolf's (1981) data also indicated that the effect of mulching on G is short-lived. The beneficial time period when using their plastic covers on bare soil surfaces appeared to be about 1 h.

An increase in nocturnal soil temperatures of upward to 2°C was found using coal dust and was dependent on the location in relation to the tree (Table III). Soil temperatures were higher under the canopy following the coal dust application and essentially unchanged in the soil region outside of the canopy influence. Turrell and Austin (1965) found the effect of trees to be significant in maintaining higher soil temperatures due to back radiation from trees. Indeed, higher soil temperatures can be maintained due to this effect. Higher soil temperatures may account for a portion of the increased radiation loss from the orchard. A 1°C increase in the average bare soil temperature results in an increase in the loss of radiation of 2.5 W m^{-2} from the orchard, provided all the energy transfer at the soil surface was lost as radiation. Other sources of radiative loss may account for the remainder of the net radiative loss, such as increased tree and air temperatures.

Sensible heat flux (H) was the only other component (besides RN) to be affected by the application of coal dust. The H relationship in Table II indicated an increase in the downward flux of sensible heat following the coal dust application. Differences in the relationship between plots due to the application were significant when H was computed using the aerodynamic method, and although not conclusive, the residual method indicated an increase in the downward flux of sensible heat. This finding may result from increased convective turbulence due to surface heating and/or to a stronger inversion developed after the coal was applied. Air temperatures at 195 cm above the bare soil surface (Table III) and above the grass alley were significantly lower following the coal dust application; near the bare soil surface they were significantly higher. Thus a larger temperature gradient existed near the canopy top on the plot treated with coal dust and led to the greater downward H. Similar findings of temperature profiles under stable stratification were found in wind tunnel observations by Ogawa et al. (1985). Their data indicated that as stability decreased, wind speed and temperature gradients near the surface decreased. However, at greater distances from the surface, the gradients increased. Their work supports the results of this study where, as stability decreased (due to the coal dust), air temperature gradients decreased near the soil surface (to about 1 m) and increased with heights > 1 m. Under conditions when H was -30 W m^{-2} on the trashy plot, the 90% CI of the predicted H on the bare soil plot before and after the coal dust application was respectively -22 to -28 W m^{-2} and -29 to -39 W m^{-2} (Table III). The increased flux of sensible heat to the orchard under these conditions was 8 W m^{-2} as determined by the aerodynamic method and 5 W m^{-2} for the residual method.

The effect of coal dust in moderating orchard climates was positive, as indicated by canopy temperature relationships (Table II). A 0.5°C increase in bud temperature due to the coal dust was found under freezing conditions (Table III). The wooden dowel and stem temperature changes resulting from the coal dust application also give support to the likelihood of a 0.5°C increase in canopy temperature.

No systematic effect on microclimatic relationships was detected when the data were analyzed separately for the three dates (9 and 17 April and 3 May). However, significant differences were evident between RN and temperature data collected before the coal dust application and at each of the three dates. Sensible heat flux appeared not to be affected by the coal dust treatment when data were analyzed separately for each date. This possibly was due to the differences in the range of data at each date compared to the range observed before the coal dust application.

CONCLUSION

Coal dust was found to moderate the orchard climate under radiative frost conditions. The degree of modification in orchard temperature (1°C) was comparable to other soil management strategies.

An increase in the loss of radiation resulted from the coal dust application. Higher soil, tree and air temperatures account for the $5\,\mathrm{W\,m^{-2}}$ increase in radiative loss from the orchard. This energy loss was compensated for by a gain in sensible heat flux to the orchard. A greater downward flux of sensible heat resulted from larger air temperature gradients near the top of the canopy. No effect of using coal dust was detected in the soil heat flux or orchard canopy storage components.

The direct effect of using coal dust on orchard climates was found in a 0.5°C increase in bud temperature.

The results of this study indicate that coal dust alters the stability of the orchard environment. Provided more time is given for the orchard system to equilibrate with the coal dust, a greater benefit from the soil in terms of heat flow could be attained. This may provide even greater protection to orchards under radiative frost conditions.

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